

Physics at the LHC

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Snowmass Day

March 9, 2001



The LHC Operation

- ❖ Commence operation $\sim 2006 \pm ?$
- ❖ pp collision at $\sqrt{s} = 14 \text{ TeV}$
- ❖ Low Luminosity period*:
 - First 3 years at $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
 - $\int L = 10 \text{ fb}^{-1}$ per year
- ❖ High Luminosity period*:
 - Subsequent years at $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 - $\int L = 100 \text{ fb}^{-1}$ per year
 - Interactions per crossing = 23

* ***subject to change***

The Physics Program

- ❖ Rich physics program at the LHC
 - From precision measurements
 - To probing for physics beyond the Standard Model
- ❖ Origin of EW symmetry breaking:
 - Full mass range sensitivity for SM Higgs
 - Sensitivity in a large parameter space for MSSM Higgs
 - Sensitive to alternate scenarios:
 - Detect structure in WW scattering amplitude
- ❖ Supersymmetry
 - Discovery straightforward for $M_{\text{SUSY}} \sim 1 \text{ TeV}$
 - The Challenge: Precise SUSY measurements

The Physics Program (2)

❖ Top Factory

- ❑ 8 million $t\bar{t}$ pairs per year at low luminosity
- ❑ Precision mass measurement ($\Delta m < 2 \text{ GeV}$)
- ❑ Detailed study of properties, rare decay searches

❖ B-Physics

- ❑ 10^{12} $b\bar{b}$ per year
- ❑ CP violation, B_s oscillations, rare decays

❖ Electroweak

- ❑ 300 million single W ($\Delta m \sim 15 \text{ MeV}$ with $\int L = 10 \text{ fb}^{-1}$)
- ❑ Anomalous gauge boson couplings

❖ QCD

- ❑ Quark sub-structure up to $\Lambda = 30 \text{ TeV}$

Higgs Bosons

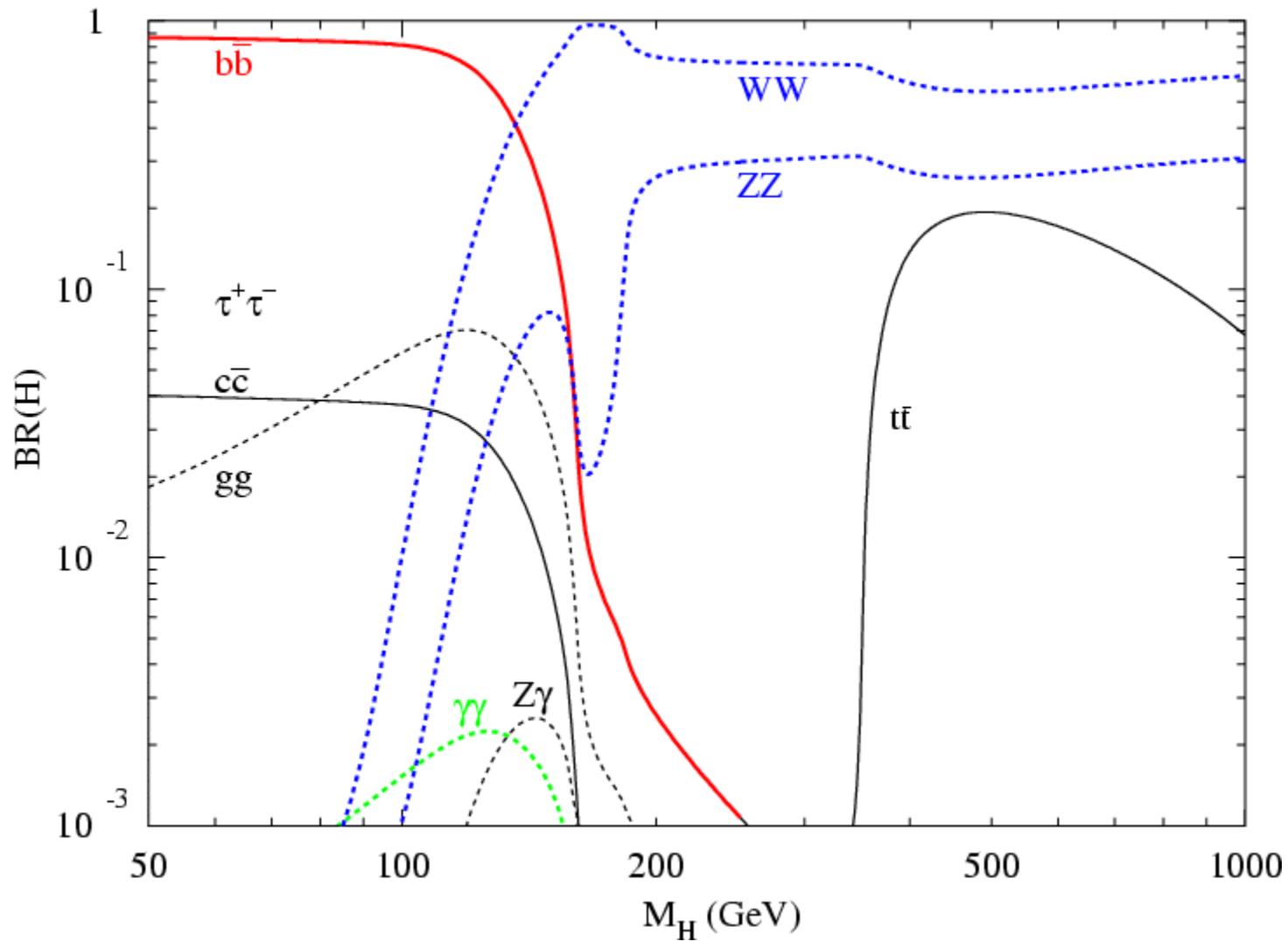
❖ Standard Model Higgs

- LEP II Limit : $m_H > 113.5 \text{ GeV}$
- Global Fit to EW data: $m_H < 200 \text{ GeV}$
- For $\Lambda = \text{Planck scale}$ $130 < m_H < 190 \text{ GeV}$
- For $\Lambda = 1 \text{ TeV}$ $50 < m_H < 800 \text{ GeV}$
- Unitarity constraints : $m_H < 1 \text{ TeV}$

❖ SUSY Higgs

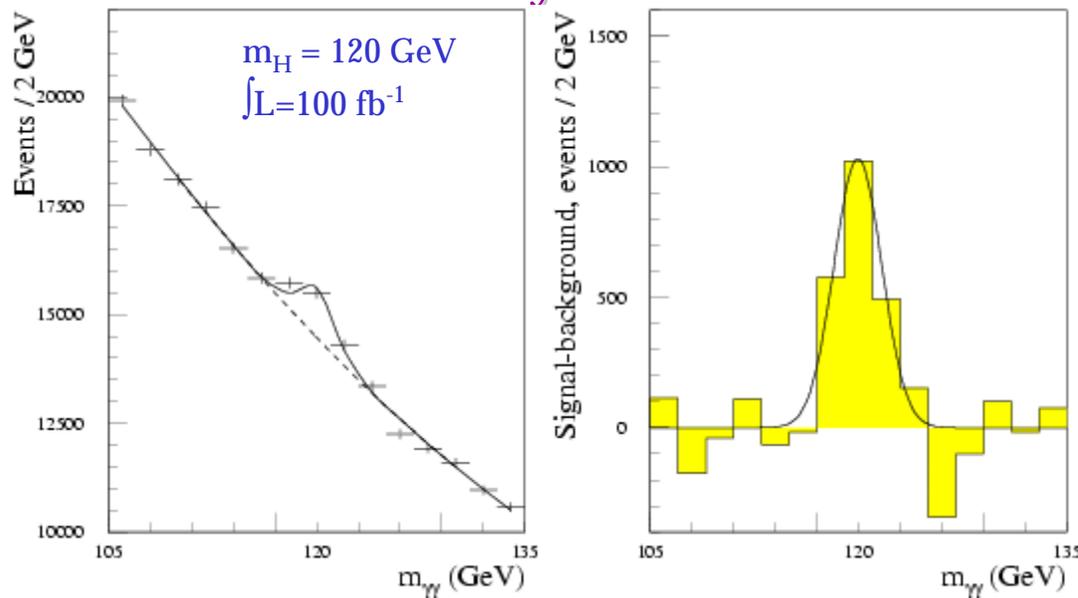
- Five physical states (h, H, A, H[±])
- m_h (lightest higgs) $< 135 \text{ GeV}$ (MSSM)
- All masses/couplings expressed in terms of ($m_A, \tan\beta$)
- Expect $\tan\beta < m_t/m_b$

SM Higgs Production



SM Higgs: $80 < m_H < 2m_Z$

- ❖ $H \rightarrow b\bar{b}$
 - Direct production hopeless
 - Extraction from associated $t\bar{t}H$ feasible
- ❖ $H \rightarrow \gamma\gamma$ (direct or associated with $W, Z, t\bar{t}$)
 - Irreducible background from diphoton production
 - $\sigma_m \sim 1\%$ dominated by detector resolution



SM Higgs: $80 < m_H < 2m_Z$ (2)

- ❖ $H \rightarrow ZZ^* \rightarrow 4 \text{ leptons}$
 - Clean signature for $m_H > 120 \text{ GeV}$
 - Backgrounds: ZZ^* , ZZ , $t\bar{t}$, $Zb\bar{b}$
- ❖ $H \rightarrow WW^* \rightarrow l\nu l\nu$
 - Cannot reconstruct the Higgs mass peak
 - Backgrounds: WW^* , WZ/ZZ , $t\bar{t}$, $W+\text{jets}$
- ❖ $WH \rightarrow l\nu l\nu$
 - Additional discovery channel, Low backgrounds
 - Couplings only to gauge bosons appear

SM Higgs : $m_H > 2m_Z$

❖ $H \rightarrow ZZ \rightarrow 4 \text{ leptons}$

- Most reliable for discovery up to 700 GeV
- ZZ continuum background reduced with hard $p_T Z$ cut

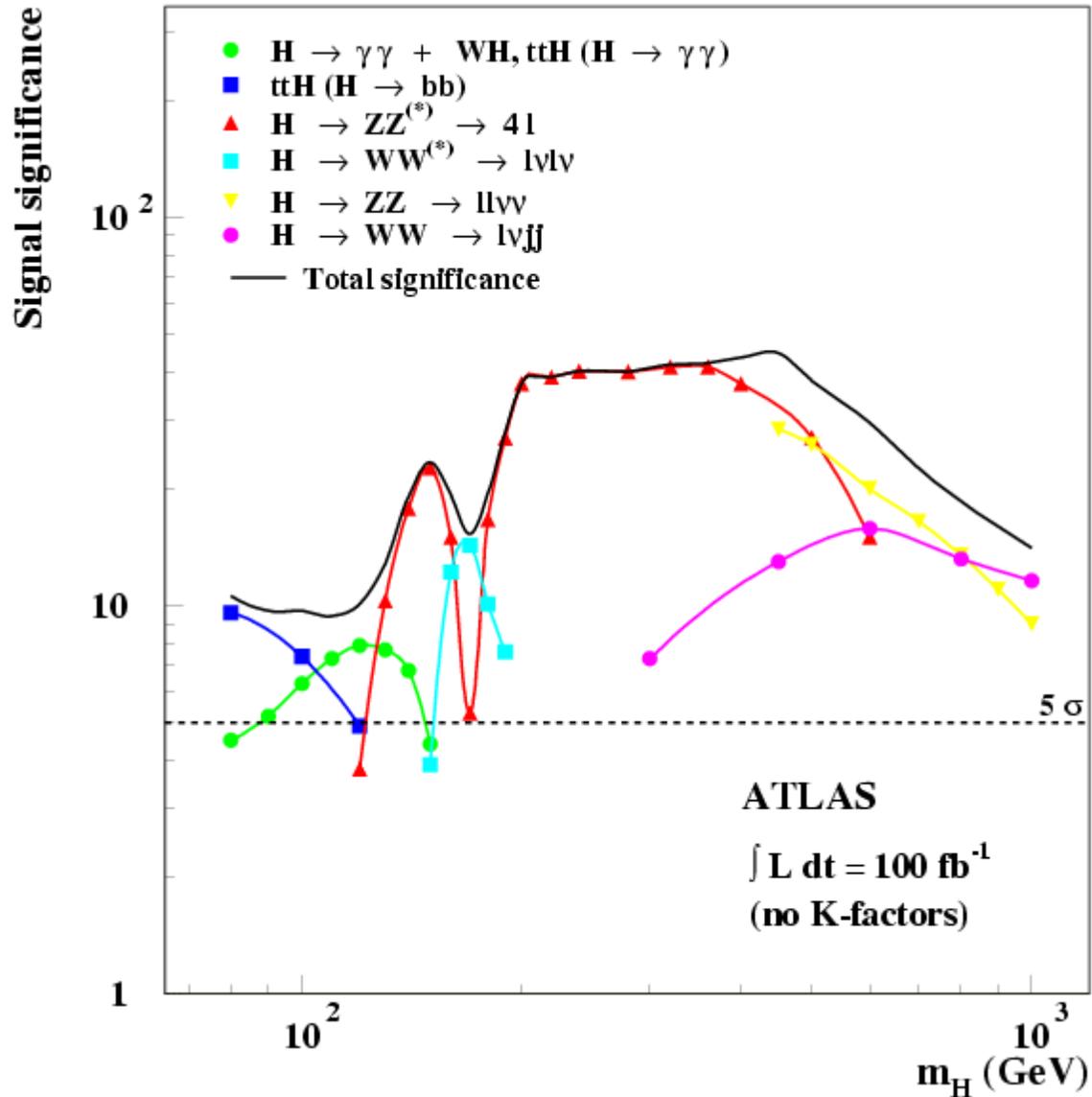
❖ $H \rightarrow ZZ \rightarrow ll\nu\nu$

- Six times larger BR than $ZZ \rightarrow 4 l$
- S/B improved with $P_T(Z)$ cut and forward jet tag
- Sensitive up to $m_H = 900 \text{ GeV}$

❖ $H \rightarrow WW \rightarrow l\nu jj$

- Backgrounds: $W+\text{jet}$, $t\bar{t}$, WW reduced with:
 - Hard $P_T(W)$ cut, $\Delta R(\text{jet-jet})$ (works well for large m_H)
 - central jet veto and forward jet tag (selects $qq \rightarrow qqH$ events)
- Sensitive for large $m_H \sim 1 \text{ TeV}$

Observability of SM Higgs



SM Higgs mass

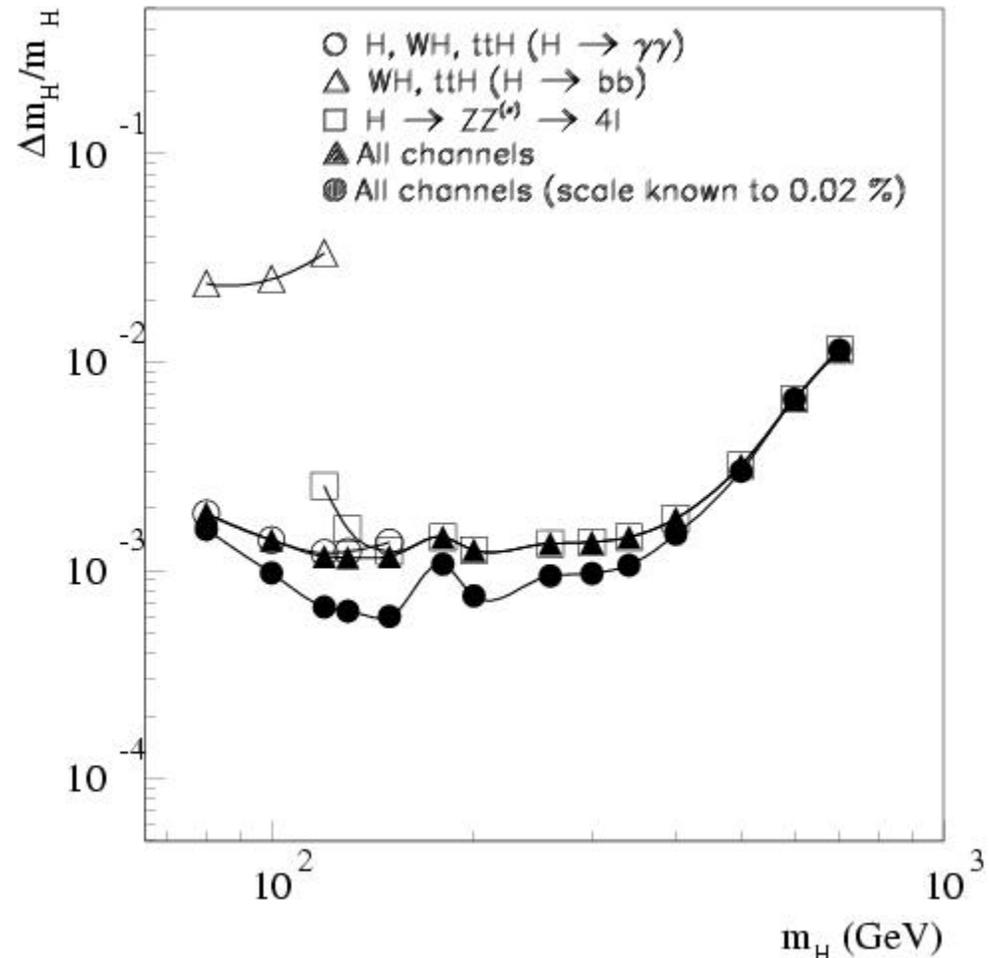
❖ $H \rightarrow \gamma\gamma$ (low m_H) and $H \rightarrow ZZ^{(*)}$ (high m_H) contribute to the mass determination.

❖ Syst. errors include:

- ❑ EM scale = 0.1%
- ❑ jet scale = 1%
- ❑ Background

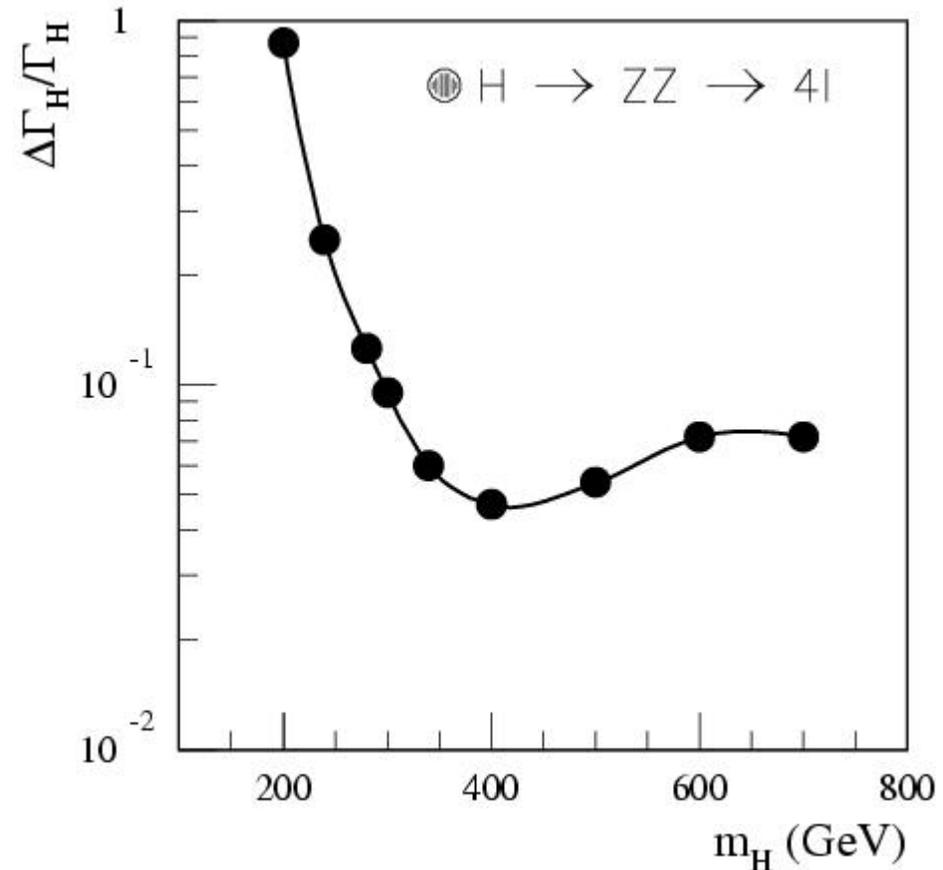
❖ For $\int L = 300 \text{ fb}^{-1}$:

$$\Delta m / m = 0.1\%$$



SM Higgs Width

- ❖ Direct measurement possible only for $m_H > 200$ GeV, where intrinsic width is comparable to detector resolution
- ❖ Measured with $H \rightarrow ZZ \rightarrow 4 \text{ leptons}$
- ❖ Sys. errors includes detector resolution obtained from Z width
- ❖ For $\int L = 300 \text{ fb}^{-1}$
 $\Delta\Gamma/\Gamma \sim 6\%$

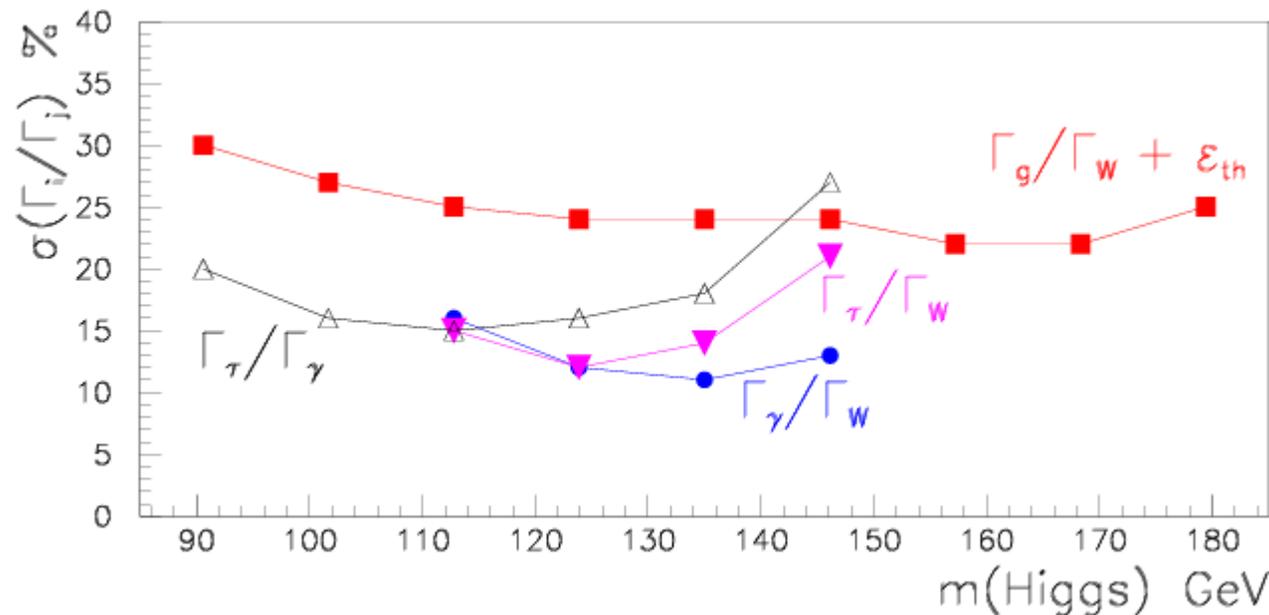


SM Higgs Couplings

Coupling ratios measured from ratios of $\sigma \cdot B$ for different channels

For example:
$$\frac{g_{Htt}^2}{g_{HWW}^2} \sim \frac{\Gamma_g}{\Gamma_W} \sim \frac{\sigma(gg \rightarrow H) \cdot B(H \rightarrow gg)}{\sigma(qq \rightarrow qqH) \cdot B(H \rightarrow gg)}$$

$WW \rightarrow H$ can be identified with forward jet tags



Work in progress (both in experiment and in reducing theoretical errors)

MSSM Higgs

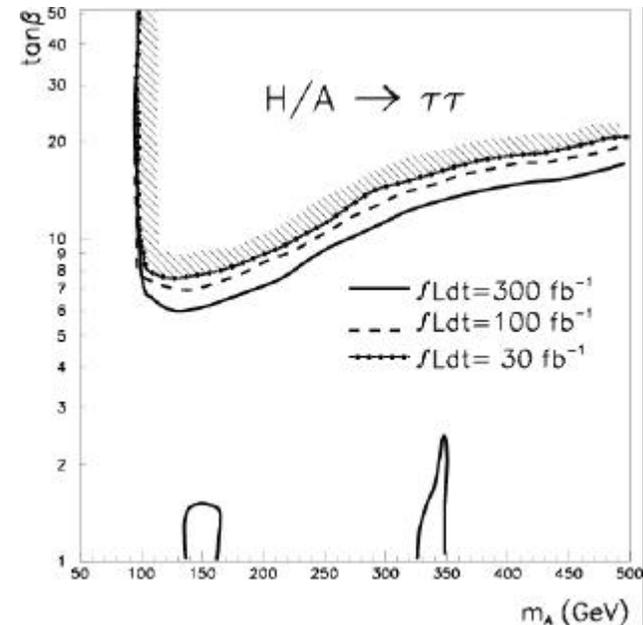
- ❖ Five physical states: h, H, A, H^\pm
 - All masses/couplings expressed in terms of $(m_A, \tan\beta)$
- ❖ Search for the MSSM Higgs is similar to SM Higgs
 - Where ever possible, the analysis use SM results after accounting for different production and decay rates.
 - SUSY masses assumed to be large (~ 1 TeV)
- ❖ $h \rightarrow \gamma\gamma$ & $(t\bar{t})h \rightarrow b\bar{b}$ observable over large parameter space
- ❖ Strong suppression of HZZ and HWW couplings
 - Enhances BR of $H/A \rightarrow \tau\tau, H/A \rightarrow t\bar{t}$

H/A → ττ

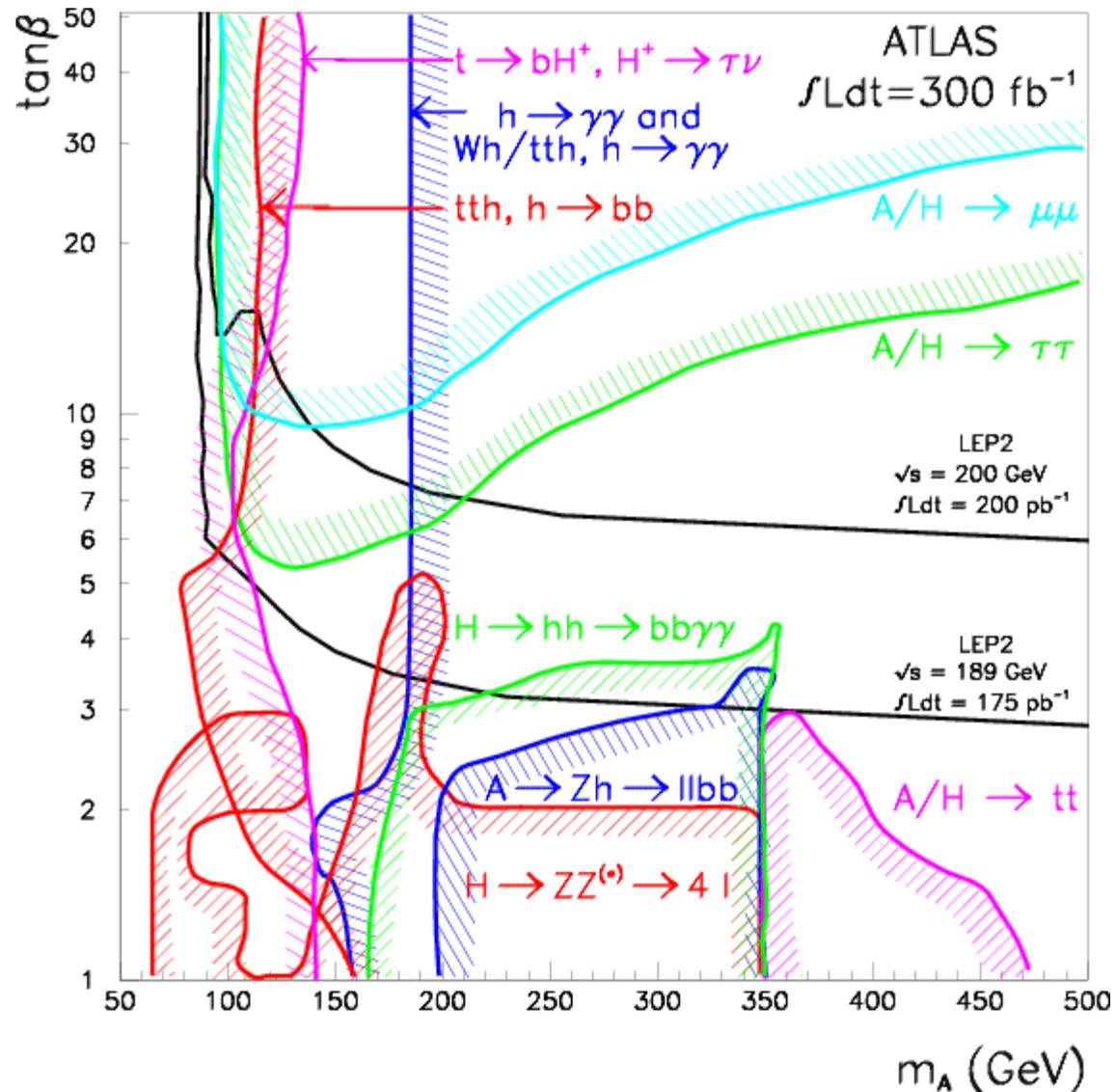
- ❖ Exploit kinematic and topological differences between:
 - Direct Production: $gg \rightarrow H/A \rightarrow \tau\tau$ (dominant at low $\tan\beta$)
 - b-jet veto to reject $t\bar{t}$ and $b\bar{b}$ backgrounds
 - Associated Production: $gg \rightarrow b\bar{b}H$ (enhanced at high $\tan\beta$)
 - One tagged b-jet (reduces W +jet and $Z \rightarrow \tau\tau$ backgrounds)

- ❖ Combining significance of both analysis improves overall sensitivity:
 $S/\sqrt{B} = 12.5$ (2.1) for $m_A = 150$ (450) GeV

- ❖ High L signal significance is ~ 50% smaller than Low L for the same $\int L$

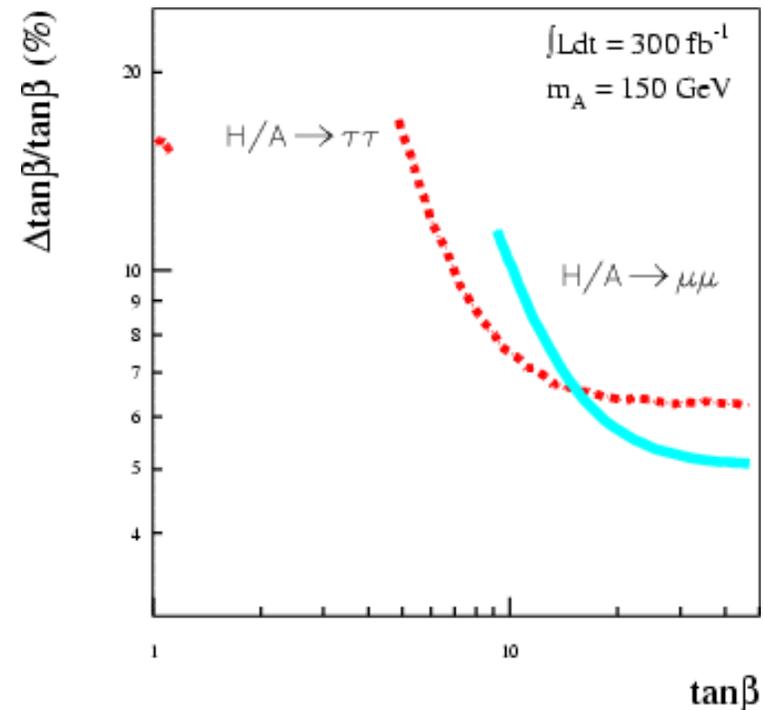
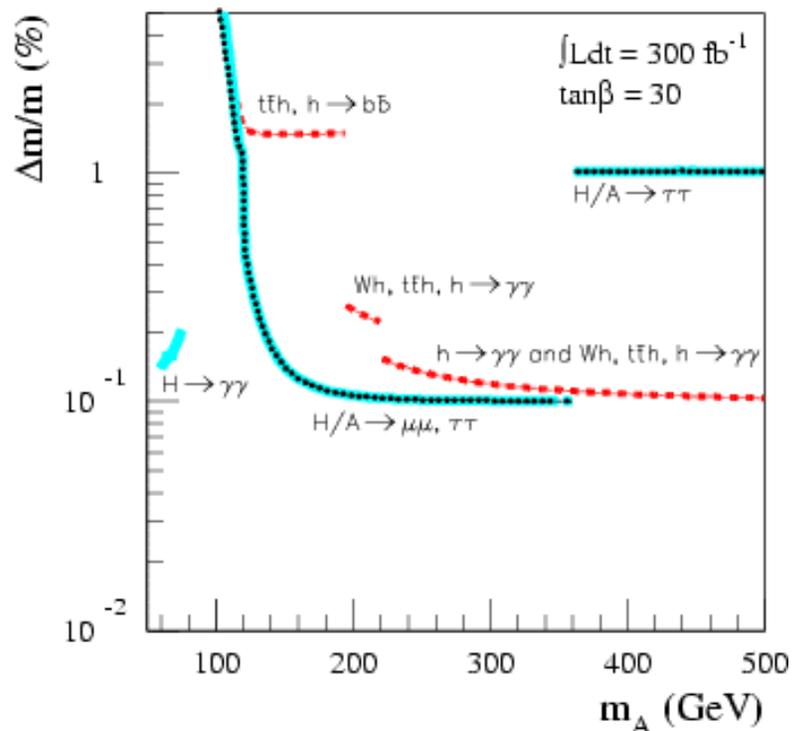


MSSM SUSY Reach



MSSM Higgs: mass & $\tan\beta$ reach

- ❖ $\Delta m \sim 0.1\%$ where $h \rightarrow \gamma\gamma$ or $H/A \rightarrow \mu\mu$ observable
- ❖ Signal rates of heavy H is sensitive to $\tan\beta$
 - $\Delta \tan\beta \sim 10\text{-}25\%$ from $H/A \rightarrow ZZ \rightarrow 4l$ (if observable)
 - $\Delta \tan\beta \sim 5\text{-}15\%$ from $H/A \rightarrow \tau\tau/\mu\mu$ (if observable)



SUSY or SM Higgs?

- ❖ Independent confirmation of SUSY
- ❖ Observation of more than one Higgs in a large fraction of the parameter space.
- ❖ $h \rightarrow b\bar{b}$ in decays of SUSY particles
- ❖ Suppressed $H \rightarrow ZZ^*$ rate
- ❖ $\Gamma_H \sim 10$ (1) GeV for SM (MSSM)
 - Measurable only for $m_H > 250$ GeV
- ❖ Enhanced $A/H \rightarrow \tau\tau$ (and maybe $\mu\mu$) rate
- ❖ Charged Higgs ($H^\pm \rightarrow tb$ or $t \rightarrow bH^\pm$) production

SUSY at the LHC

- ❖ If SUSY exists at the TeV scale
 - ❑ **gluinos and squarks strongly produced**
 - ❑ **Distinctive topological decays**
 - ❑ **Easy to discover**
 - ❑ **Precision measurements is the challenge**
- ❖ Various models considered by ATLAS & CMS:
 - ❑ m-SUGRA, GMSB, RPV models
 - ❑ Studies mostly based on fast simulation
- ❖ Main background is SUSY itself
 - ❑ Necessary to generate entire SUSY cross-section
 - ❑ + Relevant SM backgrounds

SUGRA Models

- ❖ Characterized by m_0 , $m_{1/2}$, $\tan\beta$, A_0 , $\text{sgn}(\mu)$
- ❖ SUGRA points selected by LHC for study:

Point	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$	$\text{sgn } \mu$
1	400	400	0	2	+
2	400	400	0	10	+
3	200	100	0	2	-
4	800	200	0	10	+
5	100	300	300	2.1	+
6	200	200	0	45	-

- ❖ Total SUSY cross-section:
 - ~ few pb (for $M_{\text{SUSY}} \sim 1 \text{ TeV}$)
 - ~ 1 nb (for $M_{\text{SUSY}} \sim 300 \text{ GeV}$)

Inclusive Signatures

Many complex SUSY signatures:

$$\tilde{g} \rightarrow \tilde{q}q$$

$$\tilde{q} \rightarrow \tilde{C}_1^0 q \quad \text{or} \quad \tilde{C}_2^0 q \quad \text{or} \quad \tilde{C}_1^\pm q$$

$$\tilde{C}_2^0 \rightarrow \tilde{C}_1^0 l^+ l^- \quad \text{or} \quad \tilde{C}_1^0 Z^0 \quad \text{or} \quad \tilde{C}_1^0 h$$

$$\tilde{C}_1^\pm \rightarrow \tilde{C}_1^0 l^\pm n \quad \text{or} \quad \tilde{C}_1^0 W$$

❖ Final State may consist of:

Multi Jets + Missing E_T

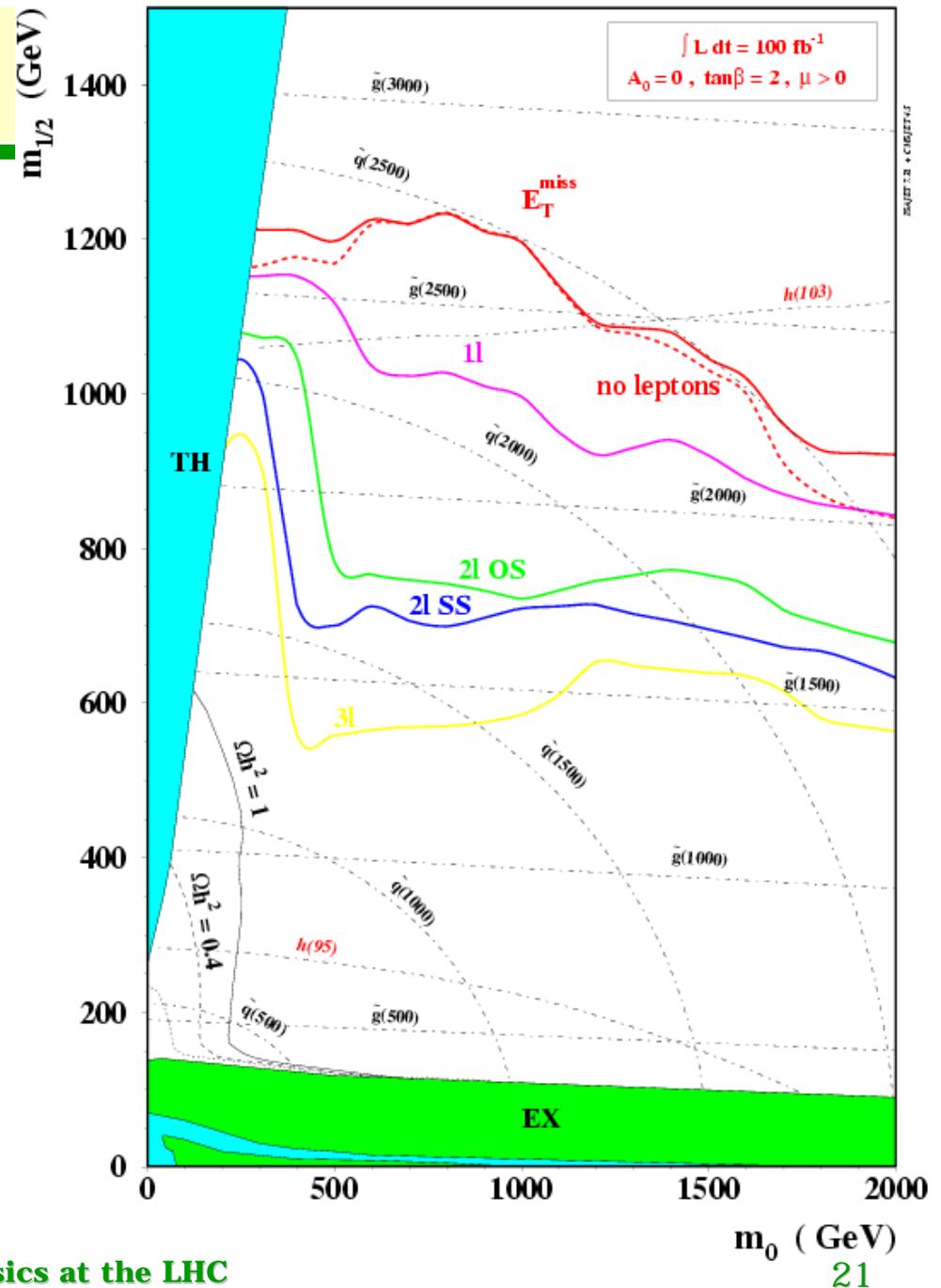
+ (n = 1,2,3,4) high P_T leptons

+ same sign (SS) lepton pairs

❖ Define Resulting Reach :

* **Require at least 10 events**

* **$S/\sqrt{B} > 5$**



Estimate of Effective Mass

$$M_{\text{EFF}} = \cancel{E}_T + \sum_{i=1}^4 E_T^i \quad (4 \text{ hardest jets})$$

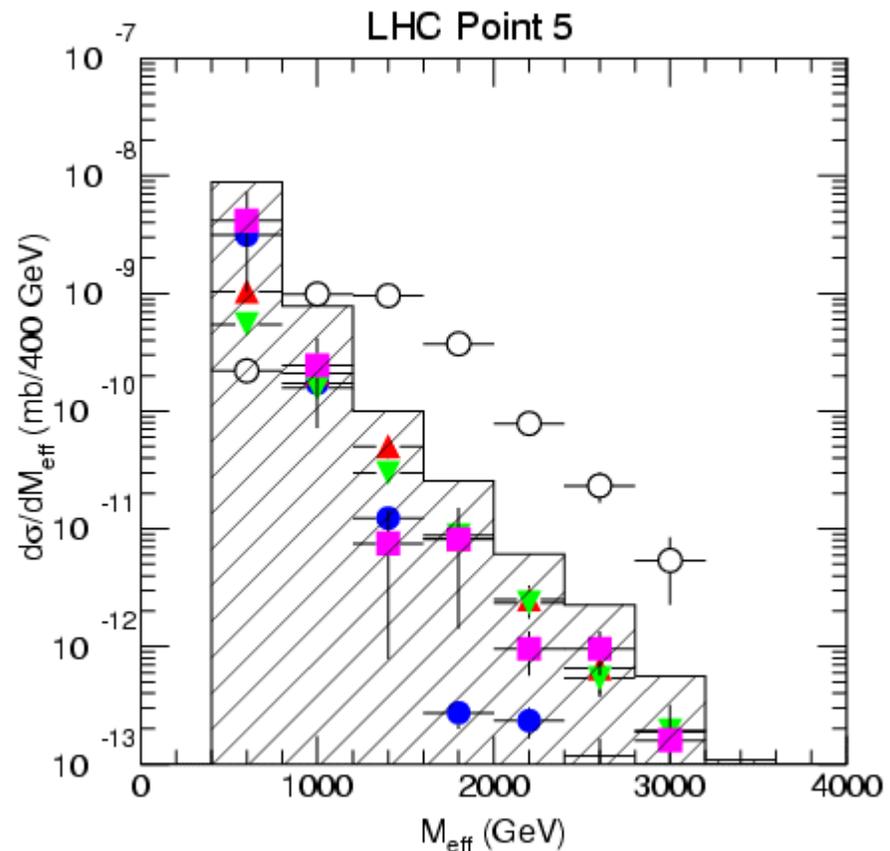
S/B ~ 10 at high M_{EFF}

Estimate $M_{\text{SUSY}} (\propto M_{\text{EFF}})$

~ 10% precision

Backgrounds modeled:

W+jet, Z+jets, $t\bar{t}$, QCD



Precision measurements

- ❖ Identify bottom of decay chain
- ❖ Measure kinematic endpoints
- ❖ Determine masses
- ❖ Make fit for model parameters

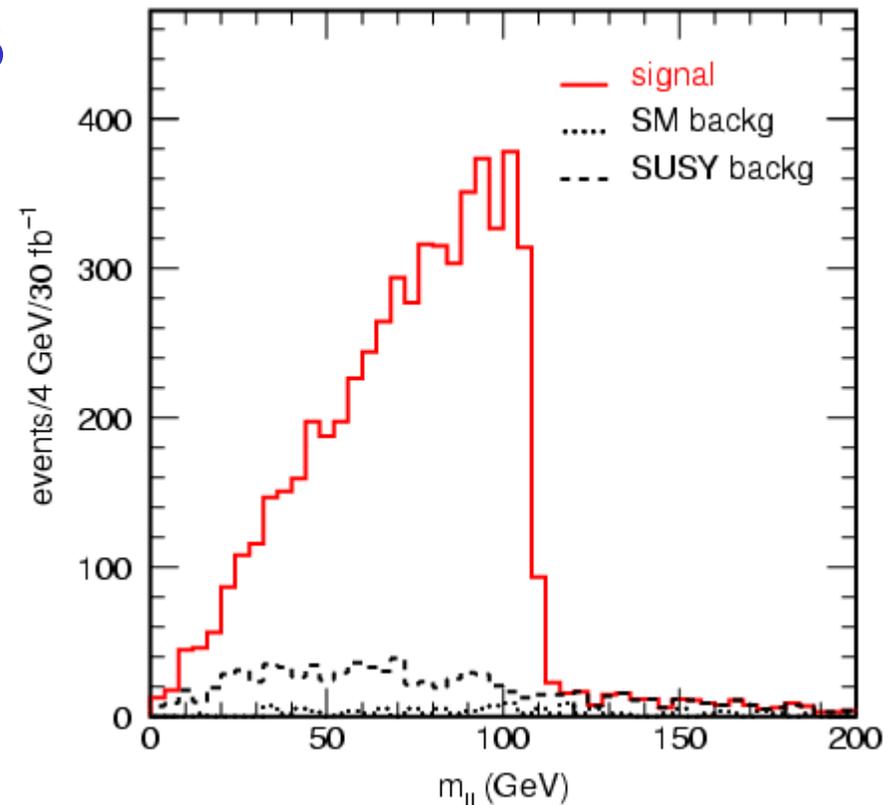
- ❖ Taking SUGRA point 5 as an example:

$$\tilde{q}_L \rightarrow \tilde{C}_2^0 q \rightarrow \tilde{l}_R^\pm l^\mp q \rightarrow \tilde{C}_1^0 l^+ l^- q$$

- ❖ Determine constraints from measuring the kinematic end points of m_{ll} , m_{lq} , m_{llq}

Dilepton Edges

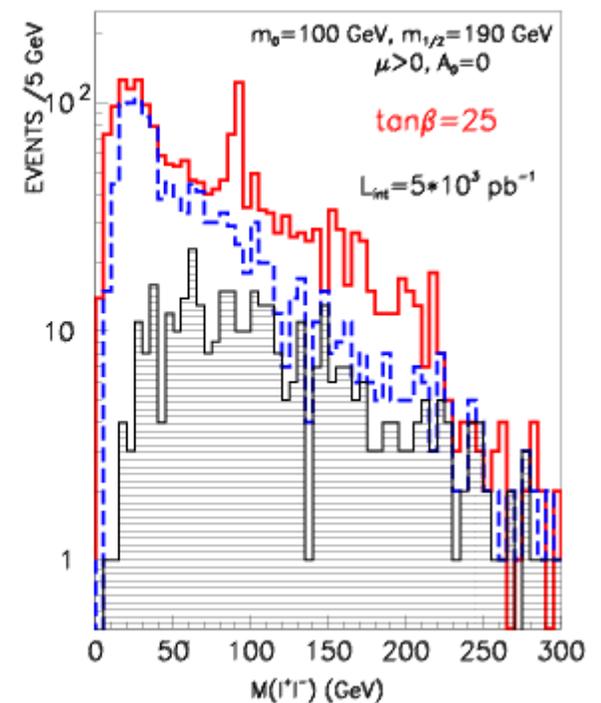
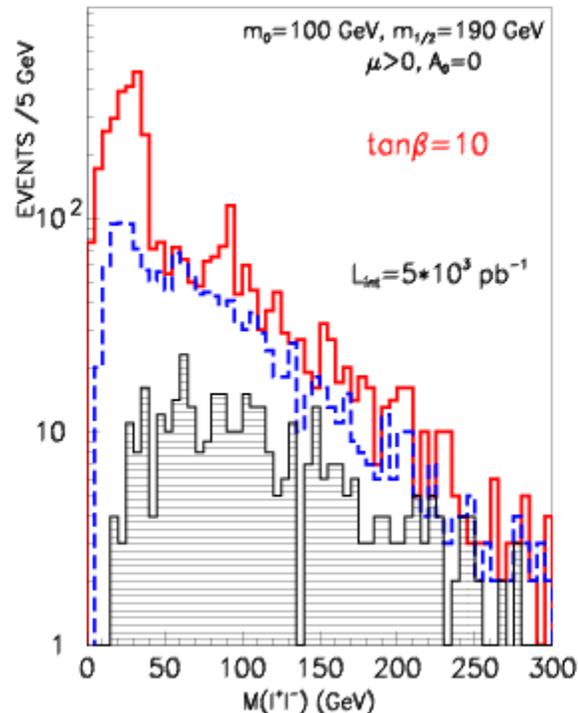
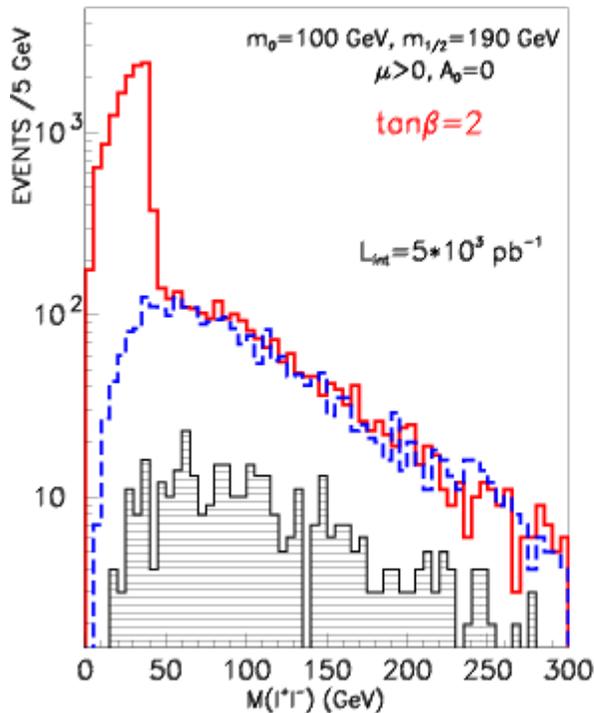
- ❖ Two body decays produces much sharper edge compared to three body decays.
- ❖ Flavour subtraction ($e^+e^- + m^+ \bar{m} - e^\pm \bar{m}$) to reduce background & combinatorials
- ❖ Z peak visible at large $\tan\beta$
- ❖ 0.1% precision edge measurement (100 fb^{-1})



Effect of $\tan(\beta)$

Comparison of same to different flavour dilepton final states:

- ❖ At low $\tan\beta$: $\tilde{C}_2^0 \rightarrow \tilde{C}_1^0 l^+ l^- (l = e, \mu)$
- ❖ At high $\tan\beta$, contributions from: $\tilde{C}_2^0 \rightarrow \tilde{C}_1^0 t^+ t^-$
 - leading to different flavour dilepton final states



lq & *llq* Edges

- ❖ Use 2 hardest jets to fit for *lq* and *llq* edges

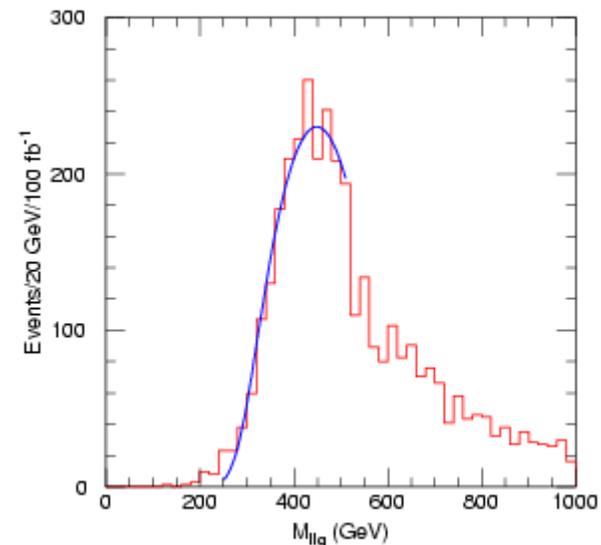
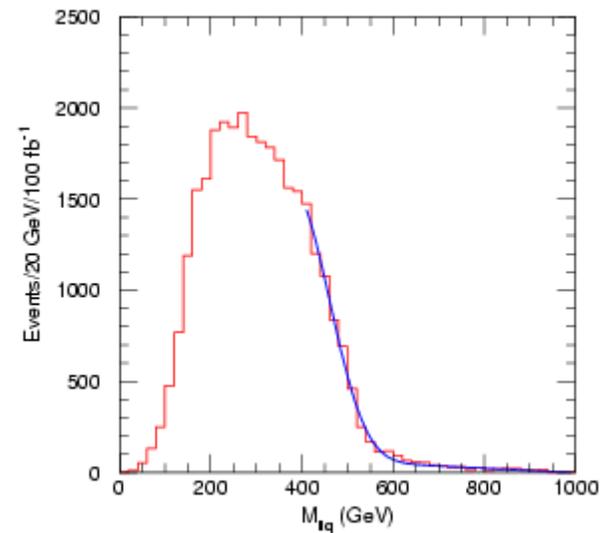
Fit to the smaller of the two *llq* mass

Error $\sim 1\%$

Lower edge from the larger *llq* mass

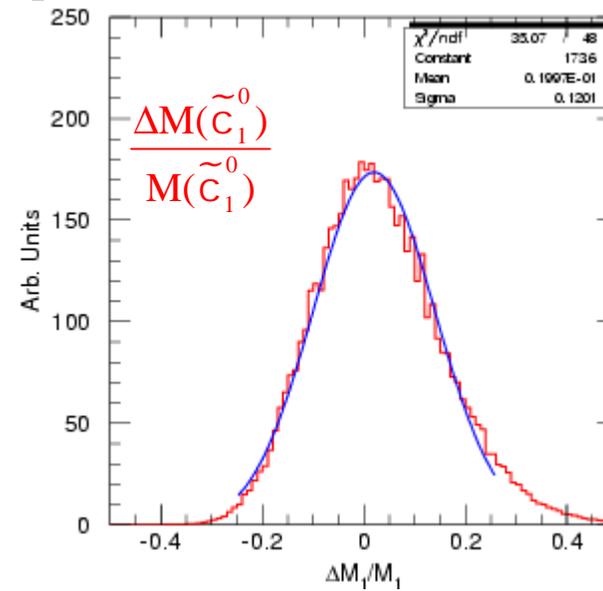
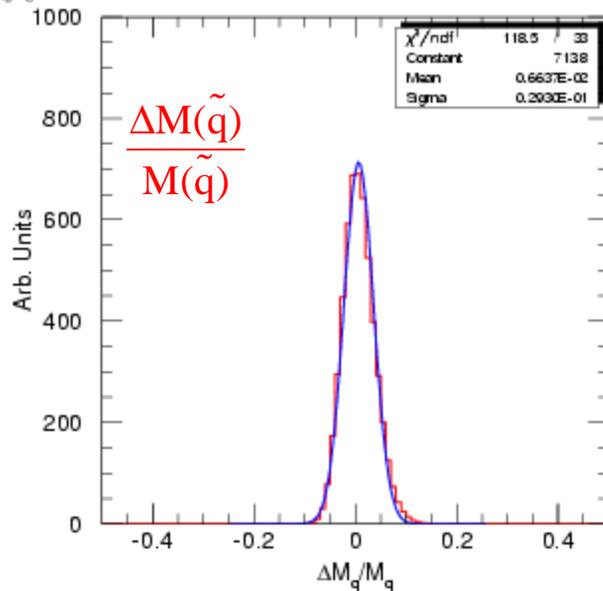
Longer tail due to FSR

Error $\sim 2\%$



Fitting for SUSY masses

- ❖ Generate random SUSY masses.
- ❖ Solve numerically for the end-points
- ❖ χ^2 fit to the measured endpoints



- ❖ Reconstruct (for SUGRA point 5 & 100 fb⁻¹): $q_L : \pm 3\%$, $\tilde{c}_1^0 : \pm 12\%$
- ❖ Reconstruct mSUGRA parameters :
 $m_0 : \pm 1.4\%$, $m_{1/2} : \pm 0.9\%$, $\tan\beta : \pm 5.5\%$

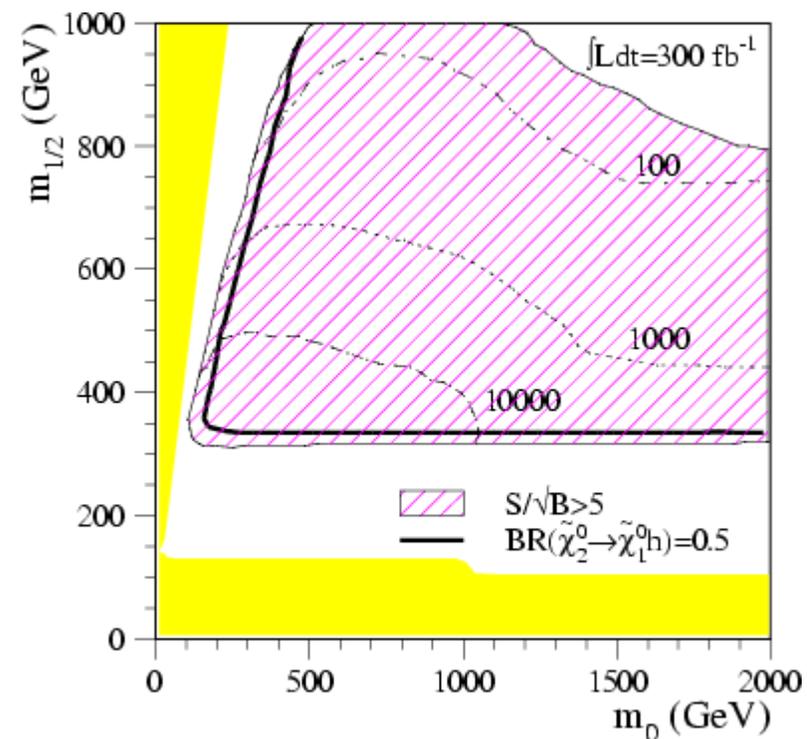
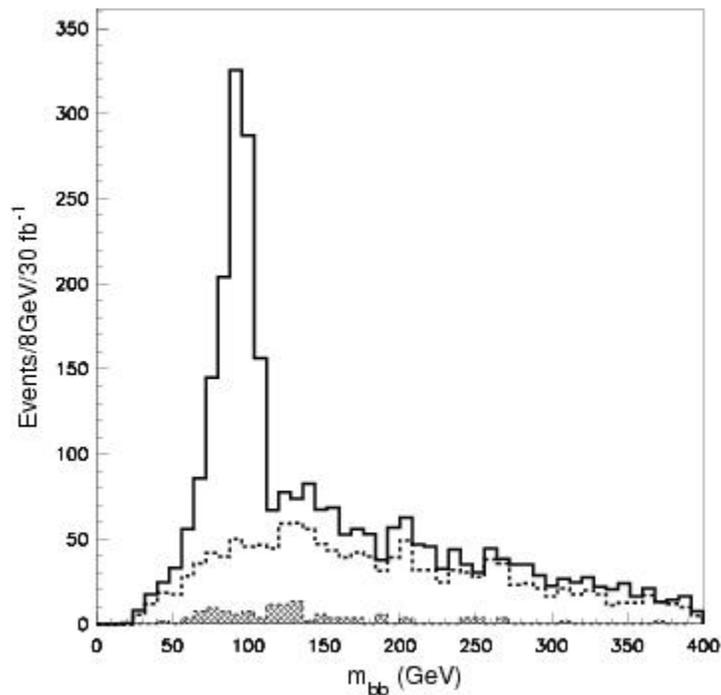
$h \rightarrow b\bar{b}$ SUGRA signatures

❖ Primary production mode: $\tilde{C}_2^0 \rightarrow \tilde{C}_1^0 + h (\rightarrow b\bar{b})$

Most of SUGRA parameter space covered.

❖ $m_0 = 400, m_{1/2} = 400, \tan\beta = 2$

$S/B \sim 4:1$ for $\int L = 30 \text{ fb}^{-1}$



Gauge Mediated Models

- ❖ Analysis approach similar to SUGRA

Reconstruct masses from kinematic endpoints

- ❖ The following points have been studied:

Λ (TeV)	M_m (GeV)	N_5	NLSP	$c\tau$ (km)	x-sec (pb)
90	500	1	C_1^0	~ 0	7.6
90	500	1	C_1^0	~ 1	7.6
30	250	3	<i>stau</i>	~ 0	23
30	250	3	<i>stau</i>	~ 1	23

P1: Two hard isolated photons : SM bkg negligible

P2: NLSP decay in tracker for fraction of events

P3: effectively 3 NLSPs ($\tilde{e}_R, \tilde{m}_R, \tilde{t}_l$) : Multiple leptons in final state

P4: Long lived sleptons are μ -like but with $\beta < 1$
Measure slepton masses using TOF

NLSP Lifetime measurement

ATLAS:

Non-pointing photons in EM Cal:

$$\Delta\theta = 70 \text{ mrad} / \sqrt{E}$$

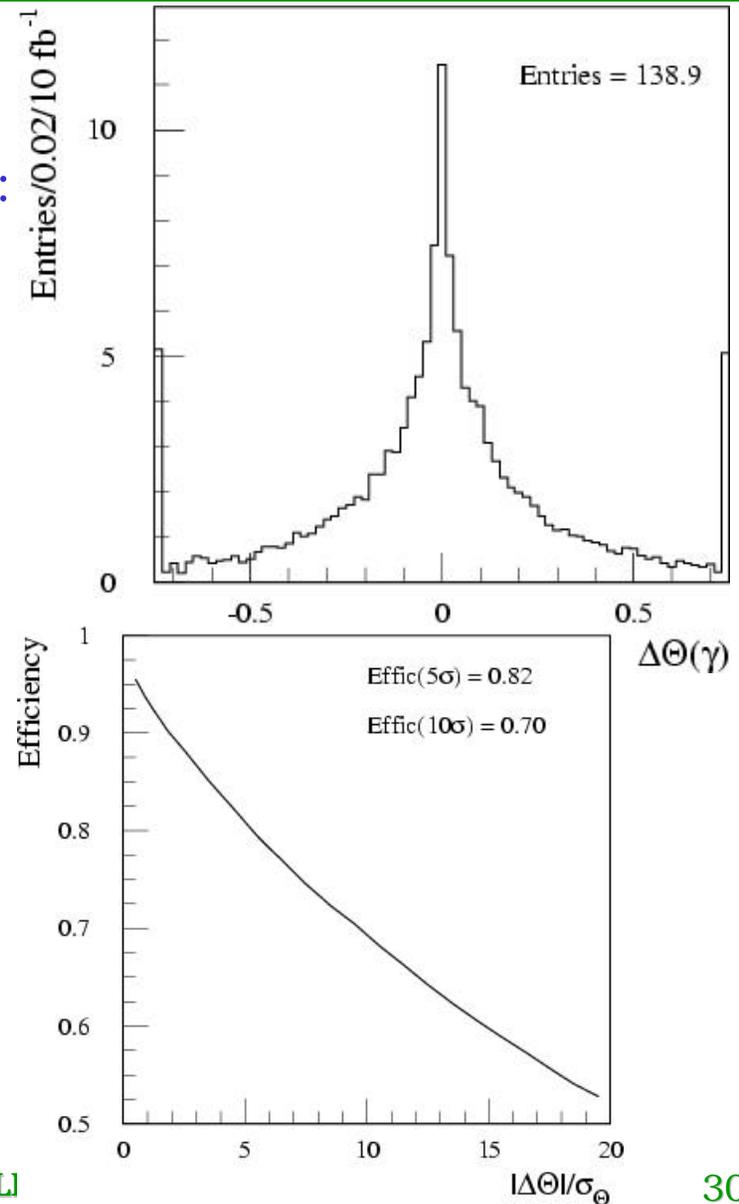
For $c\tau = 1.1 \text{ km} \ \& \ 10 \text{ fb}^{-1}$

152,000 χ_1^0 are produced

180 decay in tracker

94 detected (52% eff)

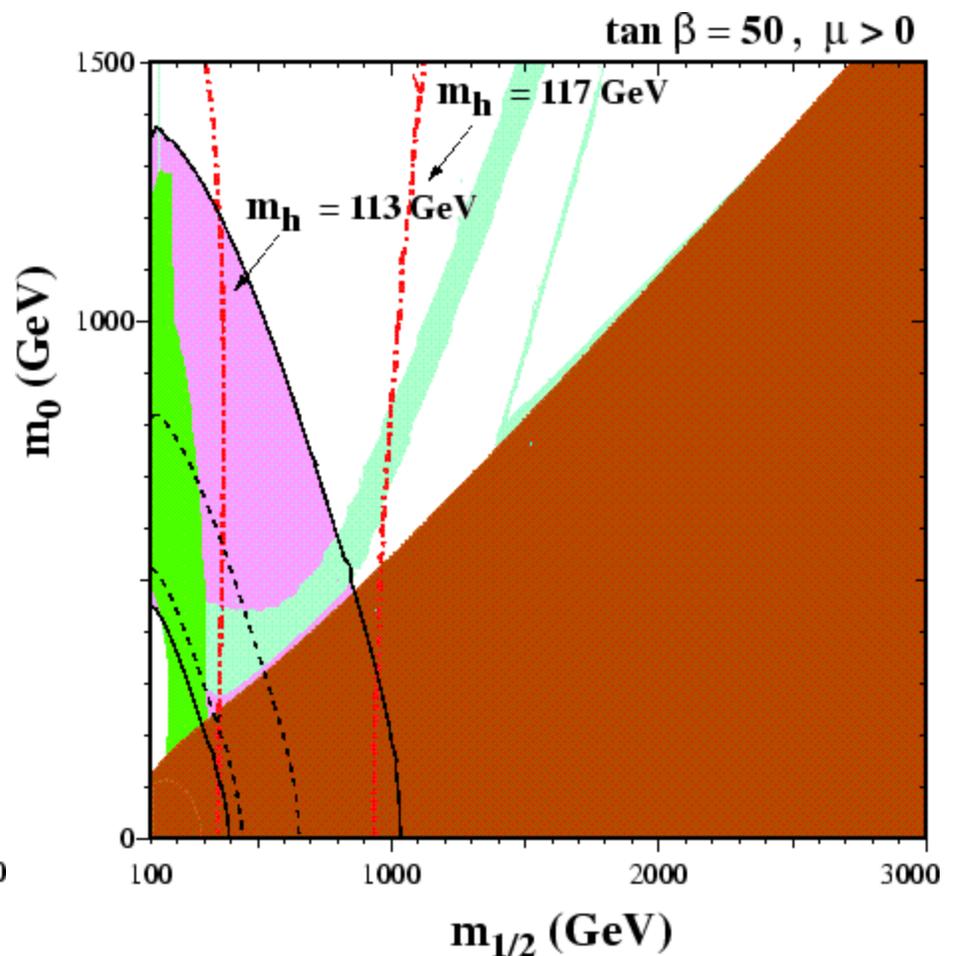
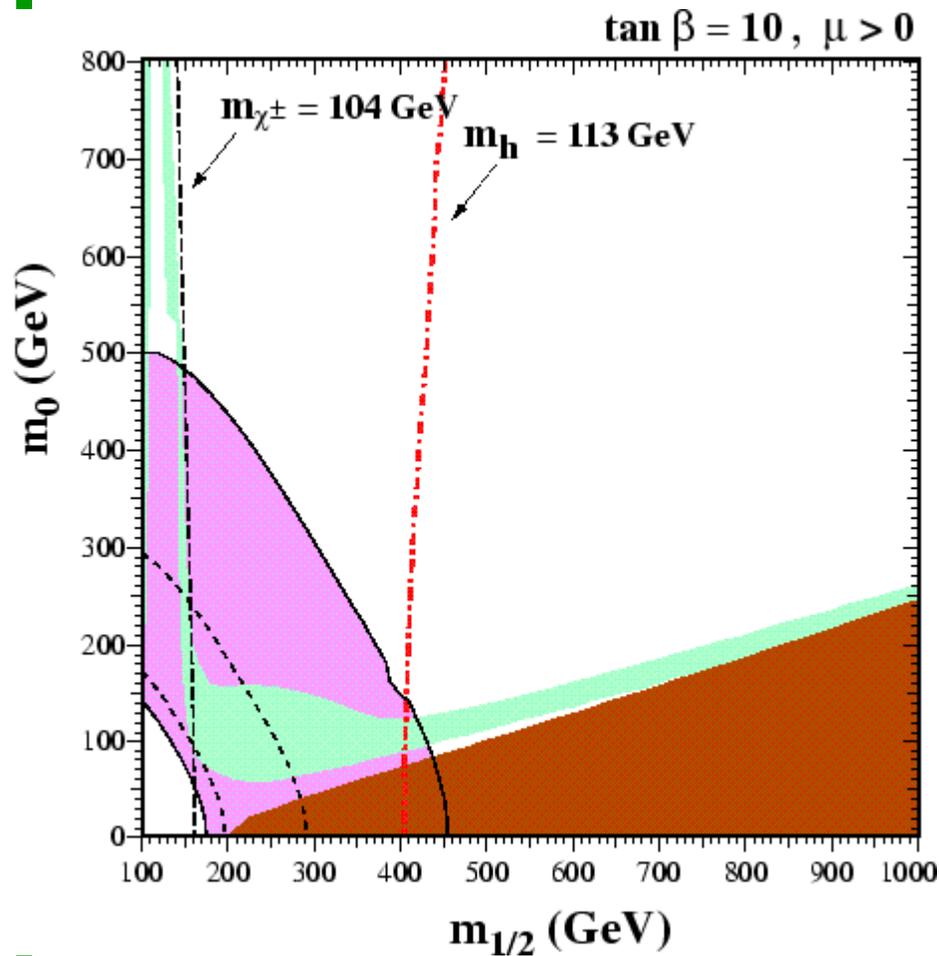
If no non-pointing photons
are detected in 30 fb^{-1} Lower limit of
 $c\tau \sim 100 \text{ km}$ at 95% CL



External Constraints?

- ❖ LEP II : $m_h > 113.5 \text{ GeV}$ favours $\tan\beta > 5$?
 - ❖ $g-2$ (E821) : suggest low sparticle masses (for $\tan\beta < 50$)
$$da_m \simeq \pm 15 \times 10^{-10} \tan\beta \left(\frac{100}{\tilde{m}} \right)^2 \left(1 - \frac{4a}{\rho} \ln \frac{\tilde{m}}{m_m} \right) = (42 \pm 16) \times 10^{-10}$$
 - ❖ $b \rightarrow s\gamma$: $2.33 \times 10^{-4} < \text{BR}(b \rightarrow s\gamma) < 4.15 \times 10^{-4}$
 - Current data favours $\mu > 0$
 - ❖ Cosmological constraints : $\Omega_\chi h^2 < 0.3$
- ➔ are consistent with each other
- ➔ constrain the allowed region of the mSUGRA space
- ➔ Should significantly narrow the playing field for LHC

Constraints on mSUGRA



Conclusion

“Experiments within the next 5-10 years will enable us to decide whether **supersymmetry**, as a solution to the naturalness problem of weak interaction, **is a myth or a reality**”

This quote appeared in Phys. Reports in 1984